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IN THE NAME OF

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Assigned to

BIOMORPHIC VLSI, INC.

for

PIXEL SELECTIVE WHITE BALANCING

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PIXEL SELECTIVE WHITE BALANCING

BACKGROUND

1. <u>Field of the Invention</u>:

The embodiments described herein relate to image processing techniques. In particular, these embodiments relate to white balancing multicolored image data.

2. <u>Related Art</u>:

Because of the tri-stimulus nature of human color perception, to reconstruct a color image of a scene it is typically necessary to recover at least three color components (typically red, green, and blue or cyan, magenta, and yellow) for each picture element (pixel) in the image. In such color imaging systems, white balance is a critical factor in perceived image quality. White balancing is a process of weighting the intensities of the individual color channels of a composite color system to achieve the greatest fidelity of the image compared to the original scene. An objective of white balancing is for a white object to be imaged with properly proportioned energies in component colors (e.g., red, green, and blue).

Red, green, and blue color channels of a typical electronic imaging device may not be in balance with one another. This imbalance is primarily due to the effects of ambient lighting. Scenes imaged under fluorescent lights may produce image pixel responses that are different from pixel responses of the same scenes imaged under incandescent light or sunlight. Also, although less likely, inaccuracies in the placement of color transmissive filters over an imaging sensor, variations in the circuitry of the imaging sensor that comprise the individual pixels, or variations in the analog-to-digital

conversion circuits (assuming separate A/D circuits are used for each color stream) may introduce color imbalance.

Various methods have been employed to achieve white balance. One method involves an inclusion of a white balance sensor (which may separate from, or combined with, a primary imaging sensor) within the system. Here, a camera operator typically points the white balance sensor at a white reference surface to extract reference color information. In another method, the imaging system may attempt to perform white balancing based upon image data extracted from a natural scene.

A system that requires the camera operator to image a white reference area to achieve proper white balance can be cumbersome due to the effects of ambient lighting on color channel balance. The operator typically performs the manual white balancing operation every time the ambient light changes. Scene based white balancing provides a more user friendly approach by utilizing information extracted from the imaging sensors independent of image data generated by imaging a white reference surface. This scene based approach places the burden of extracted color information for white balancing on the image processing algorithms not on the camera operator.

One approach to scene based white balance assumes that the average pixel intensity value for each of the color channels throughout any given scene are equivalent. In an imaging system with red, green and blue color channels, for example, one channel is typically designated as the reference channel and the other two channels are balanced to the reference reference channel. The green channel is typically designated as the reference channel due to its greater spectral responsivity over the red and blue channels and its location between red and blue channels in the visible light spectrum. Two separate gain factors are then computed

and applied to the intensity values of the red and blue channel pixels to bring them into balance with the reference green channel.

The assumption that the average pixel intensity value for each of the three channels are equal, however, is not always accurate. In a scene where the averages in the imaged object are slightly different, this assumption will cause white areas in the resulting image to take on a colored tint. Therefore, there is a need for a scene based white balancing system which provides a more accurate representation of the colors in an imaged object.

SUMMARY

Briefly, an embodiment of the present invention is directed to a system and method of processing data representative of color information extracted from an array of pixels in an imaging array. The imaging array may include a plurality of pixels which are responsive to photon energy in a distinct spectral region and provides image data. White regions in the image may be identified based upon a dispersion of intensities of photoexposure at groups of associated pixels where each pixel in a group is associated with a distinct one of the plurality spectral regions or color channels. Gain coefficients to be applied to intensities of photoexposure in the image for pixels associated with at least one of the color channels may be based upon an accumulation of the intensities of photoexposure of the pixels associated with the at least one color channel in the white regions of the image. In alternative embodiments, a degree of whiteness is associated with regions of the image captured in the imaging array. The pixel values in a particular pixel region may provide a weighted contribution to the calculation of gain coefficients based upon the degree of whiteness associated with that particular pixel region.

BRIEF DESCRIPTION OF THE FIGURES

Figure 1 shows a schematic block diagram of an electronic camera system according to an embodiment.

Figures 2A, 2B and 2C show embodiments of the imaging sensor shown in the embodiment of Figure 1.

Figure 3 is a functional flow diagram illustrating processes executed at the image processor shown in Figure 1 according to an embodiment.

Figure 4 shows a pattern of pixel data at locations in an image for illustrating a process of determining spatially neighboring pixels according to an embodiment.

Figures 5 through 8 illustrate the process of identifying which pixels are in a white region of an image for determining gain factors in the white balance step shown in Figure 3.

Figure 9 shows a functional flow diagram illustrating steps in the process of computing gain factors to be used in white balancing multiple color channels in an imaging system according to one embodiment.

Figure 10 illustrates an alternative process for identifying which pixels are in a white region of the image in the white balancing step shown in Figure 3.

Figure 11 illustrates an embodiment in which fuzzy logic is used to determine weighting factors in computing white balance gain coefficient based upon degrees of whiteness in regions of an image.

DETAILED DESCRIPTION

Embodiments of the present invention are directed to a system and method for determining gain coefficients to be applied to image data from multiple color channels in an imaging system for carrying out a white balancing process. Upon capturing an image over an exposure period, an imaging array provides data representative of intensities of photoexposure in distinct spectral regions at specific pixel locations on the imaging array. If the intensities of photoexposure of a group of associated pixels of different colors or spectral regions are proportionally equivalent, the group of associated pixels are determined to be in a "white" region of the image. The gain coefficients are determined from the intensity values of the group of associated pixels in the white regions of the image. The gain coefficients may then be applied to the pixel data from the multiple color channels to provide white balanced color image data.

Figure 1 shows a block diagram for an electronic camera system according to an embodiment. An imaging sensor 12 is preferably an electronic sensor which receives an image focused thereon by an optical system (not shown). The imaging sensor 12 may include a semiconductor substrate with transmissive filters deposited over selected locations to form pixels. Each pixel is sensitive to photoexposure in a particular spectral region defined by the transmissive properties of the transmissive filter deposited over the associated pixel location. The semiconductor substrate includes circuitry for extracting data which is representative of an intensity of photoexposure of particular pixel elements over an exposure period. The semiconductor substrate may be formed as a charge couple device (CCD) or an active pixel sensor (APS) as described in U.S. Patent Nos. 5,471,515 and 5,587,596.

Circuitry at section 14 performs functions for automatic gain control, correlated double sampling and analog-to-digital conversion functions to provide digital data representative of the intensity of the photoexposure of pixel elements at specific locations on the imaging sensor 12. For embodiments in which the imaging sensor 12 is of an APS design, the intensity values representative of the photoexposure of the pixel elements in the array may be extracted using pixel readout circuitry described in U.S. patent application Serial No. 09/274,424, entitled "Pixel Read-Out Architecture," filed on March 22, 1999, assigned to Biomorphic VLSI, Inc., and incorporated herein by reference.

An image processor 18 receives raw digital sensor data captured at the imaging sensor 12 and transforms the raw digital sensor data into a full color image. For color image data defining three colors at each pixel location and representing the pixel intensity value for each color at that pixel location with one eight bit value, each pixel location is associated with 24 bits of data to define the intensity values at each of the three spectral regions associated with the respective three colors in the image. Other embodiments may represent pixel intensity values with ten, twelve or more bits with an associated multiple of bits representing the total color information at the pixel location. Thus, for a three-color image, the image processor 18 preferably provides three overlapping arrays or sub-images of pixel data, each array containing all of the pixel intensity values for an associated color channel.

Figure 1 depicts the image sensor 12, circuitry at section 14 and image processor 13 as separate functions. In one embodiment, these functions may be performed by three corresponding separate integrated circuits. In other embodiments, the image sensor 12, circuitry at section 14 and image processor 18 may be integrated into

the same semiconductor substrate. In other embodiments, portions of the functionality of the image processor 18 may be formed in the same semiconductor substrate as the image sensor 12 and the circuitry at section 14 while other portions of the functionality may be formed in a separate semiconductor substrate.

As discussed below with reference to Figure 3, the image processor 18 executes several processes for transforming the raw digital sensor data into a full color image. According to an embodiment, the image processor 18 reads from and writes to an image buffer 16 during intermediate computations and manipulations of the image data. The image processor 18 may execute the processes for transforming the raw digital sensor data by any one of several commercially available programmable RISC processors or digital signal processors. Alternatively, the image processor 18 may have an application specific integrated circuit (ASIC) design.

A JPEG code 28 may provide data compression. Instructions executed by a microcontroller 42 may be stored in a read-only memory (ROM) 36. DRAM 38 or flash memory 34 may store data representative of images processed at the image processor 18. A memory card 30 may then store finished images, serving as an electronic "film," through a memory card interface block 32. An LCD display 26 provides a view finder while a photographer is taking pictures. A serial interface such as an RS-232 serial port or a universal serial bus (USB) (not shown) may couple the electronic camera system 10 to a personal computer system. A television encoder 20 may also couple the electronic camera system 10 to a television set 22.

Figure 2A shows an embodiment of the imaging sensor 12 which includes pixels for extracting color information in red, green and blue spectral regions. The letters R, G

and B represent locations of red, green and blue pixels, respectively. As pointed out above, pixels may be formed by depositing a transmissive filter over specific pixel locations as described in detail in U.S. patent application Serial No. 09/274,413, entitled "Color Filter Pattern," filed on March 22, 1999, assigned to Biomorphic VLSI, Inc., incorporated herein by reference. The color pattern of pixels distributed over the imaging sensor 12 is shown as having a typical Bayer pattern which is described in U.S. Patent No. 3,971,065.

Figure 2B shows an alternative embodiment of the imaging sensor 12 with a red, green, blue and white color pattern where the letters R, G, B and W represent locations of red, green, blue and white pixels, respectively. As discussed in the aforementioned U.S. patent application Serial No. 09/274,413, the white pixels may be formed in a semiconductor imaging device by maintaining an absence of a transmissive filter deposited over white pixel locations while associated transmissive filters are deposited over the red, green and blue pixel locations. Figure 2C shows an additional embodiment of the imaging sensor 12 with a four color filter pattern having different colors such as cyan, magenta, yellow and white, where the letters C, M, Y and W represent locations of cyan, magenta, yellow and white pixels, respectively.

Figure 3 illustrates a process for providing finished color images from raw digital sensor data. Steps 110 through 122 are preferably performed at the image processor 18 (Figure 1). According to an embodiment, the image processor 18 performs the steps 110 through 122 with logic circuitry formed in an ASIC (e.g., when the image processor 18 is formed in the same semiconductor substrate as the circuitry at section 14 and image

sensor 12). Such logic circuitry may be formed in an ASIC using Verilog or VHDL tools.

In other embodiments, the image processor 18 performs the steps 110 through 112 by executing algorithms encoded into computer readable instructions. In this embodiment, the image processor 18 may retrieve the computer readable instructions from the ROM 36 or DRAM 38 or the computer readable instructions may be stored in a programmable ROM (not shown) which is a part of the image processor 18. In other embodiments, the image processor 18 may retrieve the computer readable instructions from a peripheral memory device such as the flash 34, a hard disk drive (not shown) or a floppy disk drive (not shown).

A dark current correction section 104 subtracts dark current components in the raw sensor data received from the imaging sensor 12. Invariably, some of the pixels in the imaging sensor 12 may be defective. A defect concealment section 106 compensates for these defects by, for example, interpolating from neighboring pixels of the same color or replacing the data from the defective pixel with that of the nearest neighboring non-defective pixel of the same color. A defect map is preferably stored in a memory (such as the image buffer 16) to maintain a record of a defective pixel in the imaging sensor 12.

Figure 3 illustrates a process of white balancing at step 110 followed by a process of color interpolation at step 112. White balancing at the step 110 includes the calculation of gain coefficients to be applied to the pixel intensity data from each of the color channels to correct for the aforementioned problem of unbalanced color information in the image data. Processes for white balancing are discussed below with reference to particular embodiments of the present invention.

Embodiments of the imaging sensor 12 illustrated in the above mentioned U.S. Patent Application Serial No. 09/274,413 receive color intensity information at each pixel location data for a distinct color or spectral region. Therefore, at any particular pixel location color information is collected for a single color. Color information for the other color channels is not collected at the particular pixel location. The process of color interpolation at step 112 provides pixel intensity value for each of the color channels at each pixel location. This may be performed by a process of color selection whereby the imaging sensor 12 provides color information for one particular color channel at a particular pixel location, and color data extracted at adjacent pixel locations provides the color information for the other color channels as described in detail in U.S. Patent Application Serial No. 09/482,270, entitled "Color Selection for Sparse Color Image Reconstruction," filed on January 13, 2000, assigned to Biomorphic VLSI, Inc., and incorporated herein by reference. Alternatively, step 112 may perform a color interpolation process to provide image data for all colors at a pixel location as described in U.S. Patent Application Serial No. 09/482,844, entitled "Continuity Condition in Color Interpolation," filed on January 13, 2000, assigned to Biomorphic VLSI, Inc., and incorporated herein by reference. The color interpolation step 112 preferably provides a component sub-image for each color channel.

At step 114, the image processor 18 performs black level flare processing to remove any bias in the intensity values resulting from, for an example, an overexposure due to camera flash. Such black level flare processing may be performed using algorithms which are well known in the art. Each pixel of a particular color or spectral

region may also be responsive to photon energy which is outside of the spectral region associated with the pixel, introducing a color error. At step 116, the image processor 18 performs color correction to account for any such errors in the pixel data.

The image processor 18 may then perform a gamma correction process at step 118 which compensates for non-linearities in display devices. Here, the image data may be adjusted for a display onto a CRT device such as a television screen or computer monitor using a standard gamma of 2.2, as specified in the ITU-RBT.709 standard.

The processes of color interpolation at step 112 and white balance at step 110 may blur certain edges in the image. Step 120 preferably enhances edges in the image which may have been blurred in the color interpolation and white balance processing.

Finally, the image processor 18 converts the color channels of the digital image, red, green and blue, for example, to a different color space such as YcbCr color space. The embodiment of Figure 3 shows the process of white balancing at step 110 occurring prior to the process of color interpolation at step 112. Here, the white balancing process at step 110 provides image data of a single color at each pixel location corresponding with the arrangement of pixel colors on the imaging sensor 12. The process of color interpolation then converts this image data into data representative of multiple overlapping sub-images corresponding to the number of different colors of pixels on the imaging sensor 12. Each of these sub-images includes data representative of pixel intensity at each location in the sub-image for a color or spectral region associated with the sub-image. Thus, in the embodiment of the imaging sensor 12 as shown in Figure 2A, the color interpolation process at step 112 will provide data representative of three sub-images corresponding to red, green and blue.

In an alternative embodiment, the process of color interpolation may precede the process of white balancing. Here, immediately following the process of defect concealment at step 106, the color interpolation process converts the image data with pixel data for a single color at each pixel location into multiple overlapping sub-images. The process of white balancing is then performed over the data representative of all of the sub-images provided by the color interpolation process.

Embodiments of the present invention are directed to a system and method for performing the white balancing process at step 110 as shown in the embodiment of Figure 3 and, in an alternative embodiment, performing white balancing following color interpolation. Preferred embodiments of the white balancing process determine which pixels of the captured image are in a "white" region of the image. Groups of associated pixels of the different colors spanning the color space captured at the imaging sensor 12 having proportionally equivalent energy are identified as being in a white region of the image. The white balancing process calculates gain coefficients to be applied to the image data based upon the average intensity values of the pixels in the white regions of the image for each color channel. The calculated gains may then be applied to the image data over the entire image to provide a white balanced image.

In a step of identifying the white regions of the image, the white balancing process determines groups of associated pixels and compares the pixel intensity values collected at the pixel locations of the associated pixels. In the embodiment in which the white balancing process follows color interpolation, a group of associated pixels includes pixels in the different sub-images at the same overlapping pixel location. Thus, if while balancing is performed on overlapping sub-images of red, green and blue pixels, each

group of associated pixels will include a red pixel selected from a red sub-image, a green pixel selected from a green sub-image and a blue pixel selected from a blue sub-image, all being at the same overlapping pixel location in their respective sub-images. In the embodiment in which the white balancing process precedes the color interpolation process, as shown in Figure 3, the white balancing process at step 110 determines each group of associated pixels as spatially neighboring pixels by selecting pixels which are adjacent to pixels of a reference color channel.

Step 110 may process color image data stored in one or more arrays in a memory associated with the image processor 18 (Figure 1) to provide white balanced color image data. Hence, step 110 of this embodiment stores the white balanced color image having data representative of an intensity of one or more spectral regions associated with each pixel location in the imaging sensor 12 data in the memory for further processing. In other embodiments, step 110 may process image data in a streamed fashion by, for example, processing the image in sets of pixel lines or as a processing stage in a pipeline process. Here, step 110 may store in a memory, at any one time, only that image data required to process a portion of the image. The remaining image data is processed and stored during earlier or later stages.

Figure 4 shows a representation of digital image data provided by the process for defect concealment at step 106 (Figure 3) received at the white balancing process at step 110. The letters R, G and B identify the specific color channel corresponding to each pixel location in a Bayer pattern. There are twice as many green pixels as there are red or blue pixels. The reference channel is preferably chosen as green since green has a greater spectral responsivity over the red and blue, and is located between red and blue in

the visible light spectrum. Alternatively, either the red channel or blue channel may serve as the reference channel.

The pixels in the data mapping 150 may be associated into sets of spatially neighboring pixels using any one of several approaches. For example, the pixels may be initially grouped with two green pixels, a red pixel and a blue pixel as shown in grouping 152. The pixel intensity values at the green pixel locations are then compared with the intensity values at the red and blue pixel locations to determine whether the four grouped pixels are in a white spectral region. This is accomplished by determining whether the pixel intensity values are proportionally equivalent as discussed below. In one embodiment, the pixel intensity values at two green pixel locations in grouping 152 are first averaged and then compared with the pixel intensity values of the red and blue pixels in the grouping 152. Alternatively, the four pixels in the grouping 152 are formed into two sub-groupings, each sub-grouping having the pixel data for one of the green pixels in the grouping 152 and the pixel intensity values of each of the red and blue pixels in the grouping 152. The remaining pixel data shown in Figure 4 may then be partitioned into groups of four pixels and illustrated by grouping 152 for determining spatially neighboring pixels making up a group of associated pixels.

As illustrated in alternative grouping 154, the pixel intensity values for each green pixel may be initially grouped with the pixel intensity values for each of the adjacent pairs of red and blue pixels. In one embodiment, the pixel intensity values of the pair of blue pixels in the grouping 154 are averaged and the pixel intensity values of the pair of red pixels are averaged. These averaged pixel intensity values then form the basis of comparison of the intensity values of the spatially neighboring pixels in the grouping 154.

Alternatively, four sub-groupings of spatially neighboring pixels may be formed from the grouping 154 by associating the green pixel in every combination of red and blue pixels in the grouping 154. This analysis can then be repeated for determining sets of spatially neighboring pixels corresponding to each of the green pixels as described with reference to the grouping 154. While groupings 152 and 154 illustrate two particular methods for determining spatially neighboring pixels in the pixel data mapping 150, it is understood that other groupings can be used to determine spatially neighboring pixels in the white balancing process without departing from the embodiments of the present invention.

The analog-to-digital conversion circuitry at section 14 (Figure 1) preferably quantizes the exposure intensity values for each of the pixels in the imaging sensor 12 into fixed length binary words as discussed in the aforementioned U.S. patent application Serial No. 09/274,424. In an embodiment in which the intensity value for each pixel is quantized into eight bit words, the pixel intensity values at each pixel location have one of 256 discrete values from 0-255. Other embodiments may provide pixel values quantized into ten bits or twelve bits to allow each pixel intensity value to assume additional values. The image processor 18 may maintain this quantization throughout the processing steps shown in Figure 3. However, the process of white balancing described herein is also applicable to systems in which the quantization of the pixel intensity values changes from that provided by the initial analog-to-digital conversion.

Figures 5 through 8 illustrate a process of determining whether a group of associated pixels are in a white region of the image captured at the imaging sensor 12. The dark arrows on Figures 5 through 8 identify color component pixel intensity values for the group of associated pixels on a scale of 0-255, corresponding with eight bit pixel

intensity values. In this embodiment, pixels from three color channels, red, green and blue are being white balanced. However, it is understood that this process may also be applied to identifying which groups of associated pixels are in a white region in a different color space having more than three color channels or colors other than red, green and blue.

In an initial step of the process for determining whether a group of associated pixels are in a white region of the image, the intensity value of the pixel from the reference channel, being green in the presently illustrated embodiment, is preferably within a minimum and maximum intensity value defining a reference green window. If a green pixel in a group of associated pixels has a pixel intensity value which is outside of the reference green window, the group of associated pixels is not considered to be in a white region of the image. This disqualifies groups of associated pixels (from being in a white region of the image) whose green response is inaccurate due to limitations of a dynamic range of the imaging sensor 12. For example, pixels whose green component is too bright may be artificially white and skew the white balance gain factors toward green, giving the resulting image a greenish tint.

In the illustrated embodiment, the reference green window is defined as lying between the values 127 and 217. However, the reference green window may be defined by other minimum and maximum values. Figures 5, 7 and 8 illustrate cases in which the green pixel of a group of associated pixels falls within the reference green window and Figure 6 illustrates a case in which the pixel intensity value of a green pixel exceeds the upper bound of the reference green window.

Following a determination that the pixel intensity value of a green pixel is within the reference green window, pixel intensity values of the associated red and blue pixels are compared with the intensity value of the green pixel. As shown in Figures 5 through 8, a calculated red/blue window is determined based upon the intensity value of the green pixel. The calculated red/blue window preferably identifies red and blue pixel values which provide a ratio with the pixel value associated with the reference green pixel within a desired range. In the embodiment illustrated in Figures 5 through 8, the calculated red/blue window is defined as a region centered about the green pixel intensity value and extending +/- 45% of the green pixel intensity value. For example, with a green pixel intensity value of 187, the calculated red/blue window will extend from the value of 103 to 271. The red and blue pixel intensity values are within a calculated red/blue window in the cases illustrated in Figures 5 and 8.

The specific values used, including the window sizes and placements, in the example above in connection with Figures 5 through 8 are merely provided for illustration purposes. It should be understood that other values can be selected based upon the specific characteristics of the imaging sensor being used.

For those groups of associated pixels in which 1) the green pixel intensity values are within the reference green window and 2) the red and blue pixel intensity values are within the calculated red/blue window, the closeness of the red and blue pixel intensity values is evaluated. According to an embodiment, the group of associated pixels are further evaluated to determine whether the difference between the red and blue pixel intensity values is less than 30% of the entire range. In the embodiment illustrated in Figures 5 through 8, the red and blue pixel intensity values must be less than 77 apart.

Figure 5 illustrates a case in which the pixel intensity values of a group of associated pixels meet all three criteria for being selected as being in a white region of the image: the green pixel intensity value is within the green reference window; the red and blue pixel intensity values are within the calculated red/blue window; and the difference between the red and blue pixel intensity values is no greater than 30% of the entire range from 0 to 255.

Figure 6 illustrates a case in which the green pixel intensity value is outside the green reference window and the red and blue pixel intensity values are outside the calculated red/blue window. Figure 7 illustrates a case in which the green pixel intensity value is within the green reference window, but the red and blue pixel intensity values are outside of the calculated red/blue window. Figure 8 illustrates a case in which the green pixel intensity value is within the green reference window and the red and blue pixel intensities are within the calculated red/blue window. However, Figure 8 shows that the red and blue pixel intensity values are more than 77 (or 30% of the entire range from 0 to 255) apart. Therefore, the group of associated pixels shown in Figure 8 are not identified as being in a white region of the captured image.

Figures 5 through 8 illustrate one particular technique for determining whether a group of associated pixels are in a white region by evaluating a dispersion of the pixel intensity values. It should be understood by those of ordinary skill in the art that other techniques may be employed for evaluating a dispersion of the pixel intensity values of groups of associated pixels to identify pixel intensity values which are proportionally equivalent and indicative of a white region of the image.

With the green channel being the reference channel in the presently illustrated embodiment, white balancing is performed on the remaining red and blue color channels relative to the reference green channel. Gains are applied to the intensity values of all red and blue pixels in the image (i.e., all pixels not belonging to the reference color channel) as follows:

$$R_{out}(i, j) = R(i, j) * R_{bal} \qquad (1)$$

$$B_{out}(i, j) = B(i, j) * B_{bal} \qquad (2)$$

Where:

- $R_{out}(i, j)$ is the white balanced pixel intensity value for the red pixel at the location ith row and jth column location in the image;
- $B_{out}(i, j)$ is the white balanced pixel intensity value for the blue pixel at the location ith row and jth column location in the image;
- $R(i, j)$ is the pre-white balanced pixel intensity value for the red pixel at the location ith row and jth column location in the image;
- $B(i, j)$ is the pre-white balanced pixel intensity value for the blue pixel at the location ith row and jth column location in the image;

- R_{bal} is the white balancing gain coefficient applied to the pre-white balanced pixel intensity values of all red pixels in the image; and
- B_{bal} is the white balancing gain coefficient applied to the pre-white balanced pixel intensity values of all blue pixels in the image.

According to an embodiment, the white balancing gain coefficients R_{bal} and B_{bal} are determined as follows:

$$R_{bal} = G_{Wavg} / R_{Wavg} \quad (3)$$

$$B_{bal} = G_{Wavg} / B_{Wavg} \quad (4)$$

Where:

- G_{Wavg} is the average pixel intensity value of the green pixels (i.e., pixels of the reference channel) which are determined to be in the "white" regions of the image;
- R_{Wavg} is the average pixel intensity value of the red pixels which are determined to be in the "white" regions of the image; and
- B_{Wavg} is the average pixel intensity value of the blue pixels which are determined to be in the "white" regions of the image.

The values of R_{Wavg}, G_{Wavg} and B_{Wavg} may be determined using any of several different techniques applying the principle of determining which pixels are in a white region

of the image, and averaging the intensity values in each channel over all pixels in the white region. In the illustrated embodiment, R_{Wavg}, G_{Wavg} and B_{Wavg} are determined as follows:

$$R_{Wavg} = R_{Wacc} / R_{Wcount} \quad (5)$$

$$G_{Wavg} = G_{Wacc} / G_{Wcount} \quad (6)$$

$$B_{Wavg} = B_{Wacc} / B_{Wcount} \quad (7)$$

Where:

- R_{Wacc} is the accumulation of the pixel intensity values for all red pixels in the "white" regions of the image;
- R_{Wcount} is the number of red pixels in the "white" regions of the image;
- G_{Wacc} is the accumulation of the pixel intensity values for all green pixels in the "white" regions of the image;
- G_{Wcount} is the number of green pixels in the "white" regions of the image;
- B_{Wacc} is the accumulation of the pixel intensity values for all blue pixels in the white regions of the image; and
- B_{Wcount} is the number of blue pixels in the white regions of the image.

When the image data is represented in separate component sub-images in which each component sub-image defines a pixel intensity value at each pixel location for a color channel associated with the sub-image (e.g., when the white balancing process is performed after a

process of color interpolation), the values of R_{Wacc}, G_{Wacc} and B_{Wacc} may be determined by accumulating the pixel intensity values of all pixels of the corresponding sub-image which are in a white region of the image. It therefore follows that the values R_{Wcount}, G_{Wcount} and B_{Wcount} are determined by counting the number of pixels in the corresponding sub-image which are in a white region of the image.

In the embodiment in which white balancing is performed on pixel intensity data represented as single color pixel intensity values at each pixel location in the image (e.g., when the white balancing process is performed on image data extracted from a Bayer pattern imaging array prior to a process of color interpolation), the values of R_{Wacc}, G_{Wacc} and B_{Wacc} may be determined by separately accumulating for each color channel the pixel intensity values of all pixels of the corresponding of the corresponding color which are in a white region of the image. It therefore follows that the values R_{Wcount}, G_{Wcount} and B_{Wcount} are determined by counting the number of pixels of the corresponding color channel which are in a white region of the image.

The values of R_{Wacc}, G_{Wacc}, B_{Wacc}, R_{Wcount}, G_{Wcount} and B_{Wcount} may be calculated according to the following steps of pseudo code:

100 $R_{Wacc} = 0$

110 $G_{Wacc} = 0$

120 $B_{Wacc} = 0$

130 initialize G_{high}

140 initialize G_{low}

150 initialize $RB_{threshold}$

160 determine K groups sets of associated R, G and B pixels of the image data

170 for every group of associated pixels from $\ell = 1$ to K,

180   if $(G(\ell) > G_{low})$ and $(G(\ell) < G_{high})$

190   compute RB_{high} from $G(\ell)$

200   compute RB_{low} from $G(\ell)$

210   if $(R(\ell) > RB_{low})$ and $(R(\ell) < RB_{high})$ and $(B(\ell) > RB_{low})$ and $(B(\ell) < RB_{high})$

220   if $(abs(R(\ell) - B(\ell)) < RB_{threshold})$

230                 $R_{Wacc} = R_{Wacc} + R(\ell)$

240                 $R_{Wcount} = R_{Wcount} + 1$

250                 $G_{Wacc} = G_{Wacc} + G(\ell)$

260                 $G_{Wcount} = G_{Wcount} + 1$

270                 $B_{Wacc} = B_{Wacc} + B(\ell)$

280                 $B_{Wcount} = B_{Wcount} + 1$

290   endif;

310   endif;

320 endif;

330 Next ℓ

Steps 100 to 150 initialize values which determine the average intensity values of the red, green and blue pixels which are determined to be in a white region of the image according to equations (5), (6) and (7). Step 160 determines groups of associated pixels for performing a comparison of intensity values. In the embodiment in which white balancing is performed on pixel intensity data of a composite of sub-images (e.g.,

following the color interpolation at step 112), step 160 forms each group of associated pixels by selecting one pixel in each sub-image from the same pixel location. In the embodiment in which white balancing is performed on pixel intensity represented as single color pixel intensity values at each pixel location in the image (e.g., when the white balancing process is performed on image data extracted from a Bayer pattern imaging array prior to a process of color interpolation), step 160 may form the groups of associated pixels as discussed above with reference to Figure 4.

Steps 180 through 200 initialize the reference green window and the calculated red/blue window as discussed above with reference to Figures 5 through 8. Steps 210 through 280 determine whether pixels in the groups of associated pixels are in white regions of the image, and then adjust the values used to determine the average pixel intensity values of the color channels. In particular, step 180 determines whether a green pixel in the group ℓ has an associated pixel intensity value within the reference green window. Steps 180 and 190 determine the red/blue window and step 200 determines whether the red and blue pixel intensity values in the group ℓ are within the red/blue window. Step 210 determines whether the pixel intensity values of the red and blue pixels in the group ℓ are similar enough to determine that the pixels in the group of associated pixels are in a white region of the image. If so, the pixel intensity values of the red, green and blue pixels are added to the accumulation of the intensities of the red, green and blue pixels in the white regions of the image.

Figure 9 shows a functional flow diagram illustrating a process of determining the inputs for determining white balancing gain coefficients in an embodiment in which the pixel intensity data represents separate component sub-images for each color. Steps 308

through 316 determine whether the pixels in the group of associated pixels ℓ are in white regions of the image. Step 318 aggregates the pixel intensity values of the red, green and blue pixels in the white regions of the image, and determines counts of the red, green and blue pixels in the white regions of the image. These values may then be used in calculating the white balancing gain coefficients according to equations (3) through (7).

Figure 10 illustrates an alternative embodiment for determining whether a group of associated pixels are in a white region of the image. Like the embodiment illustrated above with reference to Figure 5, the embodiment of Figure 10 first determines whether a pixel intensity value of a reference channel (the reference channel being green in the presently illustrated embodiment) is within a predetermined reference window. If this condition is satisfied, a window corresponding to one of the non-reference channels, red for example, is calculated based upon the intensity value of the associated pixel in the spectral region associated with the reference channel. If the intensity value associated with the non-referenced red channel is within the calculated red window, a third window is calculated for evaluation of the pixel value associated with the remaining channel (which is blue in the presently illustrated embodiment) based upon either the reference channel pixel value, the red pixel intensity value or both. If the intensity value associated with the pixel of the remaining color channel is within this third window, it is determined that this group of associated pixels is in a white region of the image. Upon this determination, the intensity values of the group of associated pixels are accumulated as illustrated in steps of pseudocode 230 through 280.

The above-described embodiments apply the white balancing coefficients calculated above in equations (3) and (4) to pre-white balanced intensity values for red

and blue pixels in the image. In an alternative embodiment, the white balance gain coefficents calculated in equations (3) and (4) are used for selecting coefficients from a set of pre-computed white balancing coefficients. One of the objectives of a white balancing process is to respond to various lighting scenarios (incandescent, fluorescent, sunlight, etc.). In this embodiment, a set of gain coefficients are pre-computed for each anticipated lighting scenario and stored in memory such as the DRAM 38 or flash 34 (Figure 1). The white balancing coefficients for the non-reference color channels are calculated as discussed above. The white balancing step 110 (Figure 3) then selects the set of pre-computed gain coefficients that most closely matches the white balance coefficients for calculated based upon the image data. This ensures that an appropriate set of white balancing coefficients is always applied to the image data.

The embodiments described above are directed to performing white balancing on image data in three component color channels: red; green and blue. However, other embodiments may determine white balancing coefficients for image data in four or more component color channels for data extracted from imaging arrays such as those described above with reference to Figures 2B and 2C. Determining white balancing gain coefficients based upon pixel intensity values extracted from pixels in the white regions of an image remains as an objective.

Applying the subject white balancing technique to image data received from an RGBW imaging array such as that shown in Figure 2B, the green channel may still be chosen as the reference channel. Alternatively, the white channel may be chosen as the reference channel. As with the three color embodiments discussed above, pixels are associated into groups of pixels spanning the color space. In the four color embodiment,

each group of associated pixels preferably includes four pixels, each pixel providing a pixel intensity value representative of an intensity of photoexposure in a spectral region associated with one of the four color channels.

The pixel intensity values of the respective pixels in each group of associated pixels may then be used to compute windows as illustrated in Figures 5 through 8 to determine whether the group of associated pixels are in a white region of the image. Gain coefficients may then be calculated based upon these the pixel intensity values of pixels in white regions of the image.

The embodiments illustrated above are directed to identifying white regions of an image captured on an array of pixel elements based upon pre-determined relationships (e.g., ratios of intensity values) among pixels forming white regions within the image, and determining white balancing gain coefficients to be applied to pixels in all regions of the image. In alternative embodiments, white balance gain coefficients may be determined according to fuzzy logic rules which associate degrees of whiteness with regions in the image based on both pre-determined relationships (e.g., ratios of intensity values) among pixels and learned relationships among pixels. The pixels of each image region and its associated degree of whiteness may then provide a weighted contribution to the determination of the white balance gain coefficients.

Figure 11 depicts a process 400 of employing fuzzy logic rules to determine white balance gain coefficients according to an embodiment. Fuzzy rules 404a through 404e evaluate a set of neighboring pixels 402 in a region of the image (e.g., RG and B pixels spanning a color space for the imaging sensor). The fuzzy rules 404a through 404e associate the set of neighboring pixels 402 with a fuzzy set 406 where each fuzzy set 406

corresponds with a degree of whiteness in the image. An appropriate "defuzzification weight" 408 may then be applied to intensity values of the pixels in the set of neighboring pixels 402 based upon the membership of the set of neighboring pixels 402 in a fuzzy set 406 (i.e., associated degree of whiteness in the image). Several sets of neighboring pixels 402 in the image, each weighted by an appropriate defuzzification weight 408, may then contribute to the determination of white balance gain coefficients 410.

For an RGB pixel array, white balance gain coefficients determined according to the fuzzy logic of Figure 11 may still applied to the pre-white balanced intensity values for red and blue as shown in equations (1) and (2). However, the gains R_{bal} and B_{bal} may be calculated differently as follows:

$$R_{bal} = G_\beta / R_\alpha \qquad (8)$$

$$B_{bal} = G_\beta / B_\gamma \qquad (9)$$

where:

- G_β is a weighted average pixel intensity value of the green pixels in the image;
- R_α is a weighted average pixel intensity value of the red pixels in the image; and
- B_γ is a weighted average pixel intensity value of the blue pixels in the image.

The weighted average pixel intensity values for a color channel are determined by weighting the pixel intensity values of the pixels in a color channel according to the application of defuzzification weights according to a fuzzy function as illustrated with reference to Figure 11. Equations (10) through (18) below illustrate one particular example of determining the weighted average pixel intensity values according to fuzzy logic. While equations (10) through (18) illustrate one particular embodiment, it should be understood that other techniques of determining weighted the average pixel intensity values according to fuzzy logic may also be used.

$$R_\alpha = \frac{\sum_{i=1}^{R_{count}} R_i * \alpha_i}{\sum_{i=1}^{R_{count}} \alpha_i} \quad (10)$$

$$G_\beta = \frac{\sum_{i=1}^{G_{count}} G_i * \beta_i}{\sum_{i=1}^{G_{count}} \beta_i} \quad (11)$$

$$B_\gamma = \frac{\sum_{i=1}^{B_{count}} B_i * \gamma_i}{\sum_{i=1}^{B_{count}} \gamma_i} \quad (12)$$

$$\alpha_i = f_\alpha (R_i, G_i, B_i) \quad (13)$$

$$\gamma_i = f_\gamma (R_i, G_i, B_i) \quad (14)$$

$$\beta_i = f_\beta (R_i, G_i, B_i) \quad (15)$$

where:

- $f_\alpha (R_i, G_i, B_i)$, $f_\beta (R_i, G_i, B_i)$ and $f_\gamma (R_i, G_i, B_i)$ are fuzzy functions between zero and one based upon a degree whiteness in a region of the image including the group of associated pixels R_i, G_i and B_i.

In one embodiment, one or more of the fuzzy functions $f_\alpha (R_i, G_i, B_i)$, $f_\beta (R_i, G_i, B_i)$ and $f_\gamma (R_i, G_i, B_i)$ are based upon a dispersion of the intensity values R_i, G_i, and B_i about a weighted average of these intensity values as follows:

$$f_\alpha (R_i, G_i, B_i) = f_\alpha (\varphi_i) \qquad (16)$$

$$f_\beta (R_i, G_i, B_i) = f_\beta (\varphi_i) \qquad (17)$$

$$f_\gamma (R_i, G_i, B_i) = f_\gamma (\varphi_i) \qquad (18)$$

where:

- $\varphi_i = (a*R_i - \mu_i)^2 + (G_i - \mu_i)^2 + (c*B_i - \mu_i)^2$
- $\mu_i = (a*R_i + G_i + c*B_i)/(1 + a + c)$; and
- a and c are constants for scaling red and blue pixel intensity values to equivalent pixel intensities for green pixels.

According to an embodiment, the argument φ_i is indicative of a dispersion about μ_i, a weighted average of R_i, G_i, B_i. The fuzzy functions $f_\alpha (\varphi_i)$, $f_\beta (\varphi_i)$ and $f_\gamma (\varphi_i)$ may then be implemented in look-up tables associating ranges of φ_i with values from zero to one. Such an algorithm for performing white balancing may be implemented in logic similar to that illustrated in the flow diagram of Figure 9 by associating groups of pixels,

determining α, β and γ for each associated group of pixels and determining R_{bal} and B_{bal} based upon R_α, G_β and B_γ.

The embodiment illustrated above with reference to equations (10) through (18) is directed to determining R_α, G_β and B_γ from a weighted sum of all pixels in an imaging sensor. In other embodiments, the sets of neighboring pixels 402 (Figure 11) may be pre-filtered or pre-selected to be in a white region of the image using techniques such as those illustrated above with reference to Figures 5 through 8. The intensity values from each of the pre-filtered or pre-selected sets of neighboring pixels may then be weighted according to a degree of whiteness associated with the pre-filtered or pre-selected sets of neighboring pixels in the determination of R_α, G_β and B_γ.

While the description above refers to particular embodiments of the present invention, it will be understood that many modifications may be made without departing from the spirit thereof. The accompanying claims are intended to cover such modifications as would fall within the true scope and spirit of the present invention.

The presently disclosed embodiments are therefore to be considered in all respects as illustrative and not restrictive, the scope of the invention being indicated by the appended claims, rather than the foregoing description, and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.